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Review

Optimization methods applied to the design of eco-industrial parks: a literature review

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A B S T R A C T

With the growing environmental concern, there is evidence that increasing symbiotic relationship between plants in the same industrial area, highly contributes to a more sustainable development of industrial activities. The concept of industrial ecology extended to the terms of eco-industrial park (or ecopark) or industrial symbioses is the topic of extensive research since the five last years. More particularly, even if a lot of ecopark examples and realizations already exist throughout the world, a lot of ecopark proposals are in progress but not achieved. Recently, this vision leads the research community to focus on works proposing methods to optimize the exchanges of an ecopark prior to its design and construction. We find it especially interesting for the scientific community to propose a detailed paper review focused on optimization works devoted to the design of eco industrial parks.

This paper is based on a comprehensive literature search in Web of Science database for publications that listed 'industrial symbiosis' (or 'eco industrial park', or 'inter plant integration') and 'optimization'. This study is segmented into different sections with first, a description of the different concepts evoked in the literature. Then, the several types of networking in an eco-industrial park are detailed in association with the optimization methods employed to solve each problem. The following sections reviews the different objective functions that are formulated to optimally design an eco-industrial park. The last part of the paper is devoted to a critical analysis of the state of the art by proposing several routes to improve the methodologies found in the literature. Another aim of this paper review consists in finding the gaps existing in previous studies. These major gaps are found to be: the lack of multiobjective optimization studies, the absence of social/societal objectives formulation also needs to be addressed and the lack of works taking into account flexibility of ecoparks in an operational point of view.

1. Introduction and concepts

Nowadays, it is commonly admitted in the literature that several factors lead to an increasing depletion of natural resources (UNEP, 2000; UNESCO, 2009). One can cite for instance the rising of both worldwide population size (Nielsen, 2005) and urbanization. Facing this disturbing observation, a lot of research projects are now devoted to the global environmental preservation focused on industrial development based on the concept of "sustainable development" (Brundtland et al., 1987). To preserve environment while increasing business success is the main goal of industrial ecology. This concept, directly linked to sustainable development, appeared in the 1970's (Gussow and Meyers, 1970; Hoffman, 1971; Watanabe, 1972). The term of "Industrial Ecology" was then popularized by Frosh and Gallopoulos (1989) by using the analogy between natural ecosystems and industrial systems. Indeed, in natural ecosystems the use of energy and materials are optimized while wastes and pollution need to be minimized. By analogy with natural ecosystems, companies included in an EIP can be viewed as different hierarchical trophic levels in a food chain with metabolic links among them (material and energy) (Hardy and Graedel, 2002; Ashton, 2008, 2009). A more recent definition for industrial ecology has been cited by Allenby (2004, 2006): "a systems-based, multidisciplinary discourse that seeks to understand emergent behavior of complex integrated human/natural systems".

The great challenge is now to successfully perform the design of sustainable industries which are economically competitive. Building a sustainable industry is slightly linked to the term Industrial Symbiosis. According to Chertow (2000), an industrial symbiosis engages "separate industries in a collective approach to

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List of abbreviations

BBIS	bioenergy-based industrial symbiosis
CCEIS	coal-chemical eco-industrial system
CHP	cogeneration of heat and power
CWWTP	centralized wastewater treatment plant
Dp	depletion number
EIP	eco-industrial park
EIPWN	eco-industrial park water network
ENC	equivalent number of connections
GAMS	general algebraic modeling system
GEC	global equivalent cost
GHG	green house gases
GIS	geographic information system
HRSG	heat recovery steam generator
LCA	life cycle assessment
LCC	life cycle cost
LCI	life cycle inventory
LP	linear programming
MCDM	multicriteria choice decision making
MILP	mixed integer linear programming
MIND	method for analysis of industrial energy systems
MINLP	mixed integer non linear programming
NLP	non linear programming
NPV	net present value
TAC	total annual cost
WCA	water cascade analysis

competitive advantage involving physical exchange of materials, energy, water and by-products". A primordial feature of an industrial symbiosis is the collaboration offered by the geographic proximity of several companies. Most widespread manifestations of industrial symbioses are Eco-Industrial Parks. Several definitions for the concept of "eco-industrial park" can be found in the literature. However, a definition commonly adopted is "an industrial system of planned materials and energy exchanges that seeks to minimize energy and raw materials use, minimize waste, and build sustainable economic, ecological and social relationships" (PCSD, 1996; Alexander et al., 2000). At last, a basic condition for an EIP to be economically viable is to demonstrate that the sum of benefits achieved by working collectively is higher than working as a stand-alone facility (Boix et al., 2012).

In order to design sustainable stand-alone industries, a lot of tools are available including administrative, prevention or "end-of-pipe" solutions. The administrative tool consists of environmental regulations by political decrees or laws whereas a preventive approach promotes a new organization of a particular industry so as to pollute less. The end-of pipe solution is the more conventional even if it is not the most appropriate. This approach consists in decontaminating outlet streams by using several types of expensive processes (e.g. water treatment plant) so; the main drawback of this method is that environmental protection is changed into an economical cost. These traditional tools are not adequate to compensate the increasing pollution in the world and therefore, new initiatives in the fields of Industrial Ecology or Cleaner Production appeared.

According to Chertow (2004), an activity can be qualified as an industrial symbiosis if cooperating businesses include components of materials, water or energy exchange. An eco-industrial park can be represented by several types of configurations as long as it involves environmentally friendly goals and supports cooperative approaches (Chertow, 2004). In the literature, several types of cooperation have been reported, a summary of them is proposed in Table 1, the check marks are the summary from the review conducted in this study. A check mark means that at least one publication has been found to apply optimization methods to the corresponding type of cooperation.

In this table, a list of cooperative activities is constructed and the second column shows if this collaboration is involved into any optimization approach.

2. Methods and scope

The design of eco-industrial parks is a part of these recent initiatives and, alongside of several years of qualitative studies, a lot of quantitative approaches are involved during the last years. Inherently, an eco-industrial park needs to operate optimally or near its optimal conditions regarding several antagonist objectives. Despite a comprehensive review about the successful development of EIP's written by Tudor et al. (2007), there is a lack of data especially devoted to optimization in this field. This paper presents a literature review of the optimization methods applied to the development of EIP's because we find it meaningful to distinguish what has been done, in order to underscore the directions towards where future researches have to move.

This review is based on literature, and we have used the ISI Web of Science database and searched for the combination of "eco industrial park" or "industrial symbiosis" or "inter plant" and "optimization" as a topic. 44 publications in international peer-review journals were the results of this research. Fig. 1 shows the number of published articles during the last 15 years with these key words and the number of citations of the related articles.

Based on the results of this research, the publications have been identified and analyzed in order to propose a relevant outline to this paper review. The aim of this literature review is to emphasize the different methodologies developed during the last years to optimize the design of industrial symbioses and/or eco-industrial parks. First, we describe the types of symbiotic relationships that can be found in the literature (Section 3). In this part, the different methods of optimization are detailed for each type of cooperation: cooperation through the water network (Section 3.1), via energy (Section 3.2) and finally through exchanges of materials (3.3). As in any optimization problem, the following section details the objective functions considered to improve the design of an EIP in Section 4. A particular focus is made on the mathematical formulation of the different types of criteria: societal, economic, topological and environmental. Finally, a critical analysis allows to bring out the

Table 1
Types of cooperation between companies in an EIP (modified from Tudor et al., 2007).

Type of cooperation at process level	Used in optimization approaches
Exchange of materials, water and/or energy	✓
Share of units: water regeneration units, heat utilities	✓
Transformation of wastes into by-products	×
Exchanges of knowledge, human and technical resources	×
Transport of goods and people	×

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